

# MICROMECHANICAL DEVICE WITH DAMPED MICROACTUATOR

Inventors: John D. Grade  
John H. Jerman  
Joseph D. Drake

## CROSS-REFERENCE TO RELATED APPLICATION

The application claims priority to U.S. provisional patent application Serial No. 60/209,558 filed June 6, 2000, the entire content of which is incorporated herein by this reference.

## 5 SCOPE OF THE INVENTION

The present invention relates generally to micromechanical devices and more particularly to damped micromechanical devices.

## BACKGROUND

10 Micromechanical devices have heretofore been provided, and include sensors such as accelerometers, angular rate sensors and gyroscopes and optical devices such as optical switches, scanners, interferometers and tunable filters. Each of such devices includes a moving structure supported by flexural elements and is thus a spring mass system having one or more mechanical resonant modes. These modal frequencies are typically estimated through the use of finite element analysis. A mechanical quality factor or Q, which is a measure of the damping associated with the motion of the part, can be associated with each of these resonant modes.

15 For micromechanical devices fabricated in materials such as silicon, silicon dioxide, silicon nitride, or metals such as aluminum or nickel, the inherent damping of the structural material itself is extremely low. For example, electrostatic microactuators manufactured using deep reactive ion etched (DRIE) techniques often have comb gaps on the order of ten microns and thus do not provide damping in air that is sufficient for using such microactuators as positionable actuators. As a result, such devices typically have measurements of the mechanical quality factor Q in a vacuum that are typically greater than 5,000 and are potentially susceptible to external vibration or shock, especially from disturbances closely matching the frequency of one of the mechanical resonant modes of the device. It is thus important to control the damping of micromechanical devices.

25 Although viscous damping of micromechanical devices occurs from the dissipation of

energy resulting from the motion of fluid, such as air or liquid, in which the device resides, attempts to control the damping of such devices have been limited. For devices which operate at or near a mechanical resonance, such as some vibrational gyroscopes, it has been desirable to maximize the mechanical quality factor  $Q$  of the system by devising methods to package the devices in vacuum, thereby reducing the viscous damping due to air. Papers describing the effects of primarily air damping on a variety of micromechanical devices include: "Viscous Energy Dissipation in Laterally Oscillating Planar Microstructures: A Theoretical and Experimental Study", by Y.-H. Cho, et. al., 1993 Proceedings IEEE Micro Electro Mechanical Systems Workshop, Feb, 1993, pp. 93-98, and "Evaluation of Energy Dissipation Mechanisms in Vibrational Microstructures", by H. Hosaka, et. al., 1994 Proceedings IEEE Micro Electro Mechanical Systems Workshop, Feb. 1994, pp. 193-195. Neither of these papers, however, contains recommendations for modifying the geometry or fluid properties to optimize the damping of a device.

Some micromechanical devices, such as sensors, have relatively limited mechanical motion and can thus be controlled by including structures with small gaps, typically on the micron scale, in the device. In this technique, called squeeze-film damping, motion of the part causes such a gap to open and close, resulting in a fluid such as air flowing in and out of the gap. One of the many papers describing the use of holes through a structure to modify the squeeze-film effect is "Circuit Simulation Model of Gas Damping in Microstructures with Nontrivial Geometries", by T. Veijola, et. al., Proceedings of the 9<sup>th</sup> Int. Conference on Solid-State Sensors and Actuators, Stockholm, June, 1995, pp. 36-39. Unfortunately, squeeze-film damping is not generally suitable for devices having greater than a few microns of motion.

A limited amount of work has been done with linear accelerometers by packaging them in a viscous liquid, such as a silicone oil, to minimize "ringing" caused by the response of the accelerometer to shock. The practical issues involved with using fluids other than air to control or adjust damping in micromechanical devices have been discussed. See, for example, "A Batch-Fabricated Silicon Accelerometer", by Lynn Roylance, IEEE Trans. Elec. Dev., Vol. ED-26, Dec., 1979, pp1911-1917. See also International Application No. PCT/N092/00085 having International Publication No. WO 92/20096 by T. Kvisteroy et al. entitled "Arrangement for Encasing a Functional Device, and a Process for the Production of the Same". Neither of these publications, however, discuss the damping of actuators.

There is a need for a damped actuator. Unfortunately, none of the foregoing techniques has been used with actuators, and specifically with electrostatic actuators.

In general, it is an object of the present invention to provide a microactuator which is damped so as to control the resonant modes of the microactuator.

5 Another object of the invention is to provide a microactuator of the above character which is damped with a fluid other than air.

Another object of the invention is to provide a microactuator of the above character which is damped with a dielectric fluid.

10 Another object of the invention is to provide a microactuator of the above character which is damped with a liquid.

### SUMMARY OF THE INVENTION

15 The present invention provides a damped micromechanical device comprising a housing having an internal fluid-tight chamber and an electrically-driven microactuator disposed in the fluid-tight chamber. The microactuator has a movable structure capable of being moved between first and second positions at a resonant frequency. A damping fluid is disposed in the fluid-tight chamber for damping the movement of the movable structure at the resonant frequency.

### BRIEF DESCRIPTION OF THE DRAWINGS

20 The accompanying drawings, which are somewhat schematic in some instances and are incorporated in and form a part of this specification, illustrate an embodiment of the invention and, together with the description, serve to explain the principles of the invention.

FIG. 1 is a perspective view of a micromechanical device with damped microactuator of the present invention .

FIG. 2 is a perspective view of the micromechanical device of FIG. 1 with the cover removed to show the microactuator therein.

25 FIG. 3 is a top plan view of the microactuator in the micromechanical device of FIG. 1.

FIG. 4 is a cross-sectional view of the microactuator of FIG. 3 taken along the line 4-4 of FIG. 3.

FIG. 5 is a graph of the normalized rotation of the microactuator of FIG. 3 as a function of the operation frequency for several embodiments of the micromechanical device of FIG. 1.

## DESCRIPTION OF THE INVENTION

The micromechanical device of the present invention can be in the form of a device or package 9 having any suitable housing 11 provided with an internal fluid-tight chamber 12. A microactuator, and preferably an electrically-driven microactuator 13, is disposed in the chamber 12 (see FIGS. 1 and 2). A damping fluid 16 is disposed in the chamber 12 for reducing movements of the movable portion of microactuator 13 at the resonant frequency of the microactuator.

Package 9 can preferably be similar to any of the conventional packages utilized for housing integrated circuits and other semiconductor devices. One embodiment of the package 9 is shown in FIGS. 1 and 2 and is similar to a conventional dual-inline integrated circuit package. Specifically, the housing 11 of package 9 has a main body 17 formed from any suitable material such as ceramic. Internal chamber 12 is formed in body 17, which has opposite first and second end portions 17a and 17b and is shown as having the shape of a parallelepiped. The body 17 has a planar top surface 18 interconnecting first and second opposite sides surfaces 19 and further includes a front surface 22 extending substantially perpendicular to surfaces 18 and 19. Chamber 12 extends downwardly from an opening 23 provided in top surface 18 and is formed, in part, by a forward surface 26 and a bottom surface 27. The forward surface 26 extends parallel to front surface 22 and perpendicular to bottom surface 27. A seal in the form of conventional sealing ring 28 is adhered or otherwise secured to top surface 18 around opening 23. The sealing ring 28 is made from any suitable materials such as gold.

Housing 11 further includes a cover 31 made from any suitable materials such as gold-plated Kovar. The cover sealably engages body 17, by means of sealing ring 28, at opening 23. Cover 31 or lid is preferably planar in conformation and extends over the ring 28 and opening 23. A corrugated-like flexible ring 32 is formed in cover 31 for providing a central portion 33 which can move inwardly and outwardly relative to opening 23 so as to accommodate expansion and compression of the fluid within the chamber 12. Lid 31 is secured to sealing ring 28 by any suitable means such as heat bonding.

Electrical interconnect means is included in package 9 for permitting electrical connections to be made with microactuator 13 carried within. In the illustrated embodiment of the package 9, such electrical interconnect means includes a plurality of conventional pins 36 spaced along each side surface 19 of body 17. Specifically, four pins 36 are provided on each

side surface 19. It should be appreciated that the invention is broad enough to cover solder bumps and any other conventional means of the packaged integrated circuit art for making electrical contact with microactuator 13. Each pin 36 is electrically interconnected, for example by means of internal electrical leads (not shown), to a respective interconnect or bonding pad 37 disposed within chamber 12. In the embodiment illustrated, a plurality of spaced-apart bonding pads 37 are provided on bottom surface 27 within chamber 12.

The electrically-driven microactuator 13 can be of any suitable type and is preferably an electromagnetic microactuator in which the movable portion of the microactuator is driven by electromagnetic forces. More preferably, the microactuator 13 is an electrostatic microactuator in which the movable portion of the microactuator is driven by electrostatic forces. Such electrostatic microactuator 13, in general, has similarities to the microactuators disclosed in U.S. patent application Serial No. 09/464,361 filed December 15, 1999 (Our file No. A-68185), U.S. patent application Serial No. 09/547,698 filed April 12, 2000 (Our file No. A-68187), U.S. patent application Serial No. 09/727,794 filed November 29, 2000 (Our file No. A-70055) and U.S. patent application Serial No. 09/755,743 filed January 5, 2001 (Our file No. A-70217), the entire content of each of which is incorporated herein by this reference. In this regard, microactuator 13 is formed on a planar substrate 41 and has a movable structure 42, which includes a mirror holder 43, that overlies substrate 41 (see FIGS. 3 and 4). At least one and as shown a plurality of first and second comb drive assemblies 46 and 47 are carried by substrate 41 for preferably rotating movable structure 42 in first and second opposite directions about an axis of rotation 48 extending perpendicular to planar substrate 41. The axis of rotation is shown as a point in FIG. 3 and labeled by reference line 48. Each of the first and second comb drive assemblies 46 and 47 includes a first drive member or comb drive member 51 mounted on substrate 41 and a second drive member or comb drive member 52 overlying the substrate. The movable structure 42 of rotary microactuator 13 includes second comb drives 52 and is supported or suspended above substrate 41 by first and second spaced-apart springs 43 and 44.

Substrate 41 is made from any suitable material such as silicon and is preferably formed from a silicon wafer. The substrate has a thickness ranging from 200 to 600 microns and preferably approximately 400 microns. Movable structure 42 and first and second springs 53 and 54 are formed atop the substrate 41 by a second or top layer 56 made from a wafer of any suitable material such as silicon (see FIG. 4). Top wafer 56 has a thickness ranging from 10 to



200 microns and preferably approximately 85 microns and is secured to substrate 41 by any suitable means. The top wafer is preferably fusion bonded to the substrate by means of a silicon dioxide layer 57, which further serves as an insulator between the conductive top wafer 56 and the conductive substrate 41. Top wafer 56 may be lapped and polished to the desired thickness.

5 Movable structure 32 and first and second springs 53 and 54 are formed from top wafer 56 by any suitable means, and are preferably etched from the wafer 56 using deep reactive ion etching techniques. The movable structure 42 and springs 53 and 54 are spaced above substrate 41 by an air gap 58, shown in FIG. 4, that ranges from three to 30 microns and is preferably approximately 15 microns, so as to be electrically isolated from the substrate 41.

10 At least one and preferably a plurality of first comb drive assemblies 46 are included in rotary electrostatic microactuator 13 and disposed about axis of rotation 48 for driving movable structure 42 in a clockwise direction about the axis of rotation 48. At least one and preferably a plurality of second comb drive assemblies 47 are included in microactuator 13 for driving movable structure 42 in a counterclockwise direction about the axis of rotation 48. Each of the first and second comb drive assemblies 46 and 47 extends substantially radially from axis of rotation 48 and the assemblies 46 and 47, in the aggregate, subtend an angle ranging from 90 to 180 degrees and preferably approximately 180 degrees to provide a semicircular or fan-like shape to the microactuator 13. More particularly, microactuator 13 has three first comb drive assemblies 46a, 46b, and 46c and three second comb drive assemblies 47a, 47b, and 47c. The rotary microactuator 13 has a base 61 extending along a diameter of the semicircle formed by the microactuator and a substantially semicircular-shaped arc 62 forming the outer periphery of microactuator 13. A radial centerline 63 extends in the plane of substrate 41 perpendicular to base 61 and through axis of rotation 48. The first comb drive assemblies 46 are interspersed between the second comb drive assemblies 47, and the first comb drive assemblies 46 are symmetrically disposed relative to the second comb drive assemblies 47 about radial centerline 63. Mirror holder 43 is disposed at the center of microactuator 13 adjacent base 61.

25 First comb drive 51 of each of first and second comb drive assemblies 46 and 47 is mounted to substrate 41 by means of silicon dioxide layer 57. The first or stationary comb drives 51 are thus immovably secured to the substrate 41 and part of the stationary structure of microactuator 13. Each of the first comb drives 51 has a radial-extending bar 66 provided with a first or inner radial portion and a second or outer radial portion. Such stationary bars 66 each

extend to the outer periphery 62 of the microactuator 13. A plurality of comb drive fingers or comb fingers 67 extend from one side of each bar 66 in longitudinally spaced-apart positions along the length of the bar at separation distances ranging from eight to 50 microns and preferably approximately 35 microns. First or movable comb fingers 67 extend substantially  
5 perpendicularly from bar 66 and are each preferably arcuate in shape. In a preferred embodiment, piecewise linear segments are used to form the comb fingers 67 for approximating such an arcuate shape. Comb fingers 67 have a length ranging from 25 to 190 microns and increase substantially linearly in length from the inner portion to the outer portion of the bar 66. The comb fingers 67 can have a constant width along their length or vary in width along their  
10 length. For example, the comb fingers of first comb drive assembly 46a have a constant width along their length, while the comb fingers 67 of first comb drive assemblies 46b and 46c have a proximal portion formed with a width ranging from four to 20 microns and preferably approximately 10 microns and a distal portion formed with a width less than such proximal portion and, more specifically, ranging from two to 12 microns and preferably approximately six  
15 microns. Similarly, comb fingers 67 of the first or stationary comb drives 51 of second comb drive assemblies 47a and 47b have a proximal portion which is wider than the distal portion thereof, while comb fingers 67 of the first comb drive 51 of second comb drive assembly 47c are constant in width along the length thereof.

Second or movable comb drives 52 of each of first and second comb drive assemblies 46  
20 and 47 are spaced above substrate 41 by air gap 58. The movable comb drives 52 each have a construction similar to the related first comb drive 51. In this regard, each of the movable comb drives 52 has a radially-extending bar 71 provided with a first or inner radial portion and a second or outer radial portion that extends to outer periphery 62 of the rotary electrostatic microactuator 13. A plurality of second comb drive fingers or comb fingers 72 extend from one  
25 side of each of the bars 71 in longitudinally spaced-apart positions along the length of the bar. Second or movable comb drive fingers 72 are substantially similar to first or stationary comb drive fingers 67. Some of the second comb drive fingers have a constant width along the length thereof, for example, the second comb drive fingers of first comb drive assembly 46a and second comb drive assembly 47c, while the remaining second comb drive fingers have a width at their  
30 proximal portion which is greater than the width at their distal portion. The second comb drive fingers 72 are offset relative to the first comb drive fingers 67 so that second comb drive fingers

72 can interdigitate with the first comb drive fingers 67 when each second comb drive 52 is moved closer to the respective first comb drive 51.

Bars 71 of second comb drive 52 are interconnected to form movable structure 42. In this regard, bar 71 of first comb drive assembly 46a and bar 71 of second comb drive assembly 47a are joined together at their outer radial end portions by an interconnecting member or link 76. Similarly, bar 71 of first comb drive assembly 46c and bar 71 of second comb drive assembly 47c are joined at their outer radial end portions by a link 76. The bars 71 of second comb drive assembly 47a and first comb drive assembly 46c are joined together at their inner radial end portions by mirror holder 43, which is preferably centered on radial centerline 63 adjacent axis of rotation 48. As such, the inner radial portions of such bars 71 are included within the means of microactuator 13 for coupling rotatable member or mirror holder 43 to second comb drives 52. Bars 71 of first comb drive assembly 46b and second comb drive assembly 46b are joined together by an interconnecting arcuate member 77 at the respective outer radial end portions.

First and second comb drive assemblies 46 and 47 have a length ranging from 200 to 2000 microns and preferably approximately 800 microns. The first and second comb drive assemblies do not all have to be of equal length. As shown in FIG. 3, first comb drive assembly 46b and second comb drive assembly 47b are substantially smaller in length than the remaining comb drive assemblies 46 and 47. At least one and as shown all of first and second comb drive assemblies 46 and 47 are not centered along a radial extending outwardly from axis of rotation 48. In this regard, the distal ends of the first and second comb fingers 67 and 72 of each comb drive assembly 46 and 47 are aligned along an imaginary line that does not intersect axis of rotation 48 and, instead, is spaced-apart from the axis of rotation 48. Each of the first and second comb drive assemblies 46 and 47 thus resembles a sector of a semicircle that is offset relative to a radial of such semicircle. It should nonetheless be appreciated that some or all of the first and second comb drive assemblies can be centered along a radial extending through axis of rotation 48.

Means including first and second spaced-apart springs 53 and 54 is included within microactuator 13 for movably supporting structure 42 over substrate 41 and for providing radial stiffness to the second comb drives 52 and mirror holder 43. Springs 53 and 54 are symmetrically disposed about radial centerline 63 and can have a length which approximates the length of at least some of first and second comb drive assemblies 46 and 47. A bracket member



or anchor 78 is provided along base 61 of microactuator 13 for coupling first and second springs 53 and 54 to the substrate 41. The inner radial end portions of first and second springs 53 and 54 are preferably joined to anchor 78 at axis of rotation 48. Each of the springs 53 and 54 is preferably a single beam-like member having a first or inner radial end portion joined to anchor 78, so as to be coupled to substrate 41, and a second or outer radial end portion joined to a link 76, so as to be coupled to second comb drives 52 and the remainder of removable structure 42. First spring 53 extends radially outwardly from anchor 78 between movable bars 71 of first comb drive assembly 46a and second comb drive assembly 47a and second spring 54 extends radially outwardly from the anchor between movable bars 71 of first comb drive assembly 46c and second comb drive assembly 47c. The springs 53 and 54 each have a width ranging from one ten microns and preferably approximately four microns.

Second comb drives 52 of first and second comb drive assemblies 46 and 47 are each movable in a direction of travel about axis of rotation 48 between a first or rest position, as shown in FIG. 3, in which the comb fingers 67 and 72 are not substantially fully interdigitated and a second position (not shown) in which the comb fingers 67 and 72 are substantially interdigitated. Comb drive fingers 67 and 72 can be partially interdigitated, as shown with first comb drive assemblies 46b and 46c and second comb drive assemblies 47a and 47b, or fully disengaged and thus not interdigitated, as shown with first comb drive assembly 46a and second comb drive assembly 47b, when the second comb drives 52 are in their first position. When in their second position, movable comb drive fingers 72 of the second comb drives 52 extend between respective stationary comb drive fingers 67 of the first comb drives 51. Movable comb drive fingers 72 approach but preferably do not engage stationary bar 66 and similarly stationary comb drive fingers 67 approach but preferably do not engage movable bar 71.

Each of the second comb drives 52 is also movable from its first position in an opposite second direction to a third position, not shown, in which comb drive fingers 67 and 72 are spaced apart and fully disengaged. When each second comb drive 52 of the first comb drive assemblies 46 is in its second position, each second comb drive 52 of the second comb assemblies 47 is in its third position. Similarly, when each second comb drive 52 of the second comb drive assemblies 47 is in its second position, each second comb drive 52 of the first comb drive assemblies 46 is in its third position.

Each of stationary and movable comb drive fingers 67 and 72 is optionally inclined

relative to respective bars 66 and 71. That, is each such comb finger is joined to its respective bar at an oblique angle, as disclosed in U.S. patent application Serial No. 09/755,743 filed January 5, 2001, as opposed to a right angle. The inclination angle at which each comb drive finger 67 and 72 is joined to its respective bar 66 and 71, measured from a line extending normal to the bar, can range from zero to five degrees and is preferably approximately three degrees. Each movable comb drive finger 72 is further optionally offset relative to the midpoint between the adjacent pair of stationary comb drive fingers 67 between which such movable comb drive finger interdigitates when the second comb drive 52 is electrostatically attracted to the first comb drive 51, also as disclosed in U.S. patent application Serial No. 09/755,743 filed January 5, 2001. When each movable comb drive finger 72 moves to its second position between the adjacent pair of stationary comb drive fingers 67, the movable comb drive finger becomes centered relative to the midpoint between the adjacent pair of stationary comb drive fingers 67. The offset and inclination of stationary and movable comb drive fingers 67 and 72 serves to accommodate the slight radially-inward shift of the movable comb drive 52, resulting from the deflection and foreshortening of first and second springs 53 and 54, when movable structure 42 moves from its first position in which springs 53 and 54 are in a straightened position, as shown in FIG. 3, to its second position in which springs 53 and 54 are bent or deflected.

First and second pointers 81 extend radially outwardly from respective links 76 for indicating the angular position of movable structure about axis of rotation 48 on first and second scales 82 provided on substrate 41.

Electrical means is included for driving second or movable comb drives 52 between their first and second positions. Such electrical means can include a controller and voltage generator 86 electrically connected to a plurality of electrodes provided on substrate 41. Such electrodes include a ground or common electrode 87 electrically coupled to anchor 78 and thus second or movable comb drives 52, one or more first drive electrodes 88 coupled to the first or stationary comb drives 51 of first comb drive assemblies 46, and one or more second drive electrodes 89 coupled to the first or stationary comb drives 51 of second comb drive assemblies 47. A metal layer (not shown) made from aluminum or any other suitable material is provided on the top surface of top wafer 56 for creating the electrodes and any leads relating thereto. Electrodes 87-89 are electrically coupled to internal bonding pads 37 by any suitable means such as wires (not shown) and are thus electrically coupled to appropriate pins 36. Controller and voltage generator

86, typically not a part of package 9, is electrically coupled to the pins 36 and is shown schematically in FIG. 3.

Means in the form of a closed loop servo control can be included for monitoring the position of movable comb drives 52 and thus mirror holder 43. For example, controller 86 can determine the position of the movable comb drives 52 about axis of rotation 48 by means of a conventional algorithm included in the controller for measuring the capacitance between comb drive fingers 72 of the movable comb drives 52 and comb drive fingers 67 of the stationary comb drives 51. A signal separate from the drive signal to the comb drive members can be transmitted by controller 86 to the microactuator 13 for measuring such capacitance. Such a method does not require physical contact between the comb drive fingers 52 and 67. Alternatively, where microactuator 13 is used in an optical system, as in the instant application, a portion of the output optical energy coupled into the output fiber can be diverted and measured and the drive signal from the controller 86 to the microactuator 13 adjusted so that the measured optical energy is maximized.

The optical microswitch of package 9 is similar to the optical microswitch disclosed in U.S. patent application Serial No. 09/464,361 filed December 15, 1999. In this regard, a micromachined mirror 96 is coupled to microactuator 13 and extends out of the plane of the microactuator. More specifically, micromirror 96 is secured to microactuator 13 by a post preferably formed integral with the mirror 96 and micromachined separately from microactuator 13. The post is joined at its base to mirror holder 43 by any suitable means such as an adhesive. Micromirror 96 has a reflective face or surface 97 and is rotatable by microactuator 13 about axis of rotation 48.

Microactuator 13 is secured to bottom surface 27 of body 17 adjacent forward surface 26 by an adhesive or any other suitable means. Micromirror 96 extends substantially parallel to forward surface 26 and mirror face 97 faces the forward surface 26. An optically clear window can be provided in body 17 so that laser light can pass through front surface 22 and forward surface 26 and thus impinge on mirror face 97. Although a clear glass window can be utilized to couple the laser light into package 9, in the one preferred embodiment shown in FIGS. 1 and 2 a collimating lens such as a GRIN lens 98 is carried by body 17 to collimate the optical beam and to provide a fluid-tight seal between internal chamber 12 and the environment outside package 9. GRIN lens 98 is soldered or otherwise secured inside a tube formed integral with a

Kovar end plate 101 brazed to front surface 22 of package body 17. GRIN lens 98 has an outer surface 99 and an inner surface (not shown) that is spaced from mirror face 97 a distance equal to the focal distance of the lens 98.

A damping material or fluid is disposed within internal chamber 12 for damping the movement of movable structure 42 during the operation of optical switching package 9. One or more filling holes 103 are provided in body 17 and/or lid 31 for introducing the damping the fluid into chamber 12. As shown, a plurality of two filling holes 103 extend through body 17 and onto bottom surface 27. Filling holes 103 are preferably gold plated. In another embodiment of (not shown), a Kovar or other metal tube is provided in body 17 adjacent to GRIN lens 98. The tube is accessible at front surface 22 of package body 17 for filling internal chamber 12.

Damping fluid 16 is particularly suited for damping the movement of movable structure 42 and thus micromirror 96 carried thereby at the resonant frequency of such structures relative to the stationary structure of microactuator 13. Such resonant frequency is a function of the mechanical quality factor  $Q$  of the microactuator 13. If the dominant dissipation mechanism between stationary and movable comb drives or electrodes 51 and 52 is Couette flow, then such mechanical quality factor  $Q$  is inversely proportional to the viscosity of the damping fluid.

Although any suitable damping material can be utilized, a damping fluid is preferred. The viscosity of the damping fluid is chosen such that the mechanical quality factor  $Q$  of the microactuator 13, when immersed within the damping fluid in internal chamber 12, preferably ranges from 0.3 to 20 and more preferably ranges from 0.5 to three. When the mechanical quality factor  $Q$  is at such levels, undesired spikes in the rotational motion of the movable structure 42 of microactuator 13 are minimized.

A high-viscosity gas, a low-viscosity fluid or any suitable energy dissipating material can be used for damping microactuator 13. Preferred damping fluids have a viscosity greater than the viscosity of air. The viscosity of the damping fluid can be chosen over a range of at least four orders of magnitude, given reasonable ability to select the amount of damping required for a given structure of the actuator. In one preferred embodiment, the damping fluid is a liquid.

The damping fluid is preferably a dielectric fluid, that is a substantially insulating fluid, and is typically a dielectric liquid. Since the force produced by an electrostatic actuator is proportional to the magnitude of the dielectric constant of any fluid filling the gap between the

electrodes of the actuator, in this instance the gap between stationary comb drive fingers 67 and movable comb drive fingers 72, an increase in force of the microactuator can be provided by increasing the dielectric constant of the damping fluid. The relative dielectric constant of many dielectric fluids is many times greater than the dielectric constant of air, thus providing the same increase in force from a similar microactuator immersed in air for a given voltage and electrode geometry. The dielectric constant of the damping fluid is preferably greater than two and more preferably ranges from three to ten.

The damping fluid can be either a nonpolar fluid or a polar fluid. The dielectric constant of a fluid tends to increase with increasing polarity of the fluid. Hence, it can be advantageous to provide damping fluids, preferably damping liquids, with higher polarities. In another preferred embodiment, the damping fluid can be a super-critical fluid at the operational temperature of microactuator 13 and at the pressure in internal chamber 12 during such operation.

At least one optional drag-inducing member can be carried by movable structure 42 for producing drag on the movable structure as it moves between its first and third positions. In this regard, at least one and as shown a plurality of drag-inducing members or fins 106 are provided on arcuate member 77 of movable structure 42. Additional fins 106 are also provided at the outer radial end portions of movable bars 71 of first comb drive assembly 46b and second comb drive assembly 47b. Stationary drag-inducing members or fins 107 can optionally be mounted on substrate 41 in the vicinity of movable fins 106. As shown in FIG. 3, stationary fins 107 are disposed adjacent the movable fins 106 on arcuate member 77 and the outer radial end portions of such movable bars 71 discussed above. Fins 106 and 107 preferably extend substantially perpendicular to the direction of travel of movable structure 42 and are preferably disposed in the vicinity of each other. It is advantageous to minimize the mechanical clearance of fins 106 and 107 so as to maximize their effect. Such non-interdigitated fins can be provided which have sufficient clearance to be fabricated, yet as they move pass each other during motion of movable structure 42 the gap between such fins is less than the when-fabricated clearance between the fins. It should be appreciated that fins 106 and/or 107 can be provided at other locations on microactuator 13 and be of other shapes and sizes and be within the scope of the present invention. Furthermore, in other embodiments of the invention, such damping fins can be fabricated in structures which are not part of the electrostatic drive mechanisms of microactuator 13 such that a voltage difference does not exist between the movable and stationary fins when



microactuator 13 is being operated.

In operation and use, after fabrication of microactuator 13 and the attachment of micromirror 96 to mirror holder 43, the microactuator 13 is attached to bottom surface 27 in the manner discussed above. Lid 31 is attached to body 17 by means of sealing ring 28. Chamber 12 is filled with the appropriate damping fluid by means of filling holes 103 and the chamber 12 is then sealed by press fitting a plug, or soldering or welding a lid, to the exterior end of the filling holes 103. In the embodiment where a metal fill tube is provided adjacent GRIN lens 98, chamber 12 is filled by means of such tube with the damping fluid. The tube is then crimped or welded shut to contain the damping fluid within package 9.

Once package 9 is plugged into place or otherwise mounted into a suitable optical system, for example adjacent the ends of one or more optical fibers in a telecommunication system, and electrically coupled by means of pins 36 to a suitable controller and voltage generator 86, the package 9 can be used for switching laser light between the one or more optical fibers in the manner disclosed in U.S. patent application Serial No.09/464,373 filed December 15, 1999 (Our file No. A-68184), the entire content of which is incorporated herein by this reference. As part of this operation, mirror holder 43 can be rotated in opposite first and second directions of travel about axis of rotation 48 by controller 86. Suitable voltage potentials to first and second drive electrodes 88 and 89 can range from 20 to 250 volts and preferably range from 60 to 180 volts. Microactuator 13 is capable of +/- six degrees of angular rotation, that is a rotation of six degrees in both the clockwise and counterclockwise directions for an aggregate rotation of twelve degrees, when such drive voltages are utilized. Mirror holder 43, and thus micromirror 96, can be stopped and held at any location in such range of motion.

The utilization of a damping fluid within package 9 serves to damp the resonant modes of the microactuator 13. The rotation of movable structure 42 about axis of rotation 48 was studied as a function of the frequency of operation of microactuator 13. The graph in FIG. 5 plots the normalized rotation of movable structure of 42 as a function of frequency for several test cases. As set forth therein, an initial test of microactuator 13 was performed utilizing air as a damping fluid. The mechanical quality factor Q of microactuator 13 was calculated to be approximately 20 when operated in air, which has a viscosity at room temperature of approximately 190 uP. The microactuator 13 had an in-plane fundamental resonant frequency of 700 Hz and an out-of-plane resonant frequency of 2350 Hz when so tested in air. The

increased vibration amplitude at integer sub-harmonics of these resonances is due to the nonlinear nature of the drive force.

Microactuator 13 was then tested using several damping fluids having a viscosity greater than air. Specifically an immersion liquid sold by Cargille Laboratories of Cedar Grove, New Jersey, known as Cargille immersion liquid, Formula Code 4501, and diethylbenzene (DEB). The Cargille immersion liquid had a viscosity of 1.4 cP, as measured by a falling ball viscometer, and the diethylbenzene had a measured viscosity of 0.6 cP. Couette flow would predict a mechanical quality factor  $Q$  for microactuator 13 of approximately 0.25 in the Cargille fluid and a mechanical quality factor  $Q$  of approximately 0.60 in diethylbenzene, in each case neglecting the change in mass due to fluid motion. The resonant frequency for the Cargille fluid was calculated to be 375 Hz with a mechanical quality factor  $Q$  of 0.22 and the resonant frequency for the diethylbenzene was calculated to be 349 Hz with a mechanical quality factor of 0.66. After such test, package 9 was drained and microactuator or motor 13 was rinsed in isopropyl alcohol and dried. The frequency response of microactuator 13 was then measured again in air. As shown in FIG. 5, the utilization of such damping fluids in package 9 served to reduce the mechanical quality factor  $Q$  to an acceptable level and thus damp the microactuator 13 at its resonant modes.

As can be seen, when damping fluids with sufficient viscosity are utilized, the drag induced by the relative motion between the comb drive fingers 67 and 72 is sufficient to substantially damp the resonance of microactuator 13. In addition, since desired damping fluids are also denser than air, when movable structure 42 is immersed in the fluid, the inertial forces on the movable structure are reduced due to the buoyancy of the movable structure in the fluid. For example, the inertial forces on movable structure 42 made from silicon, which has a density of approximately 2.3 gm/cc, are reduced by approximately eighty percent when the structure 42 is immersed in a damping fluid such as perfluorodecalin having a density of approximately 1.92 gm/cc.

Other suitable damping fluids, not identified on FIG. 5, include neon, d-limonene, octamethyltrisiloxane, t-octylamine and ethoxy-nonafluorobutane. Neon, which has a viscosity at room temperature of approximately 315 uP, compared to the 190 uP viscosity of air at room temperature, is particularly suitable if only a small increase in damping is required for microactuator 13 or another micromechanical device. If a small decrease in damping is desired,

for example with parts where squeeze-film damping predominates, the use of hydrogen with a viscosity of approximately 90 uP is suitable.

The relative dielectric constant of the fluid was calculated by taking the square of the ratio of voltages required to achieve 50% of the full deflection at low frequency. The Cargille immersion liquid had a dielectric constant  $\epsilon$  of 2.44 and diethylbenzene had a dielectric constant  $\epsilon$  of 3.45. The Cargille immersion liquid thus provided an increase in microactuator force of approximately 2.44 and diethylbenzene provided an increase in microactuator force of approximately 3.45, in each case, relative to the force produced by microactuator 13 when operated in air.

Optional fins 106 and 107 provide additional drag on movable structure 42 so as to further damp the resonant modes of the movable structure 42 during operation of microactuator 13 and optical package 9. As movable fins 106 pass stationary fins 107, increased fluid flow is provided in internal chamber 12. Specifically, fins 106 and 107 increase the turbulence of the fluid flow within chamber 12 and thus increase the drag on movable structure 42.

Although the fluid-damped microactuator of the present invention has been shown as being part of a optical microswitch, it should be appreciated that a fluid-damped microactuator can be provided in a variety of other optical components. Further, a fluid-damped microactuator of the present invention can be utilized in other than telecommunications systems. For example, such microactuators can be utilized in data storage systems, for example magneto optical data storage systems. It should also be appreciated that the drag-inducing members of the present invention can be used in undamped microactuators, for example microactuators or other microdevices operated in air. The damping techniques disclosed herein can be used in combination with the damping techniques disclosed in U.S. patent application Serial No. \_\_\_\_\_ filed contemporaneously herewith (Our file No. A-70529), the entire content of which is incorporated herein by this reference. In addition, the damping fluids hereof can also be used with devices other than actuators.

As can be seen from the foregoing, a microactuator has been provided which is damped so as to control the resonant modes of the microactuator. The microactuator is damped with a fluid other than air and is preferably damped with a dielectric fluid. Nonpolar or polar fluids can be used as the damping fluid. The damping fluid can be any suitable liquid. The damped microactuator hereof is suited for moving structures throughout a broad range of motion to a

variety of locations, and holding such structures at such locations, particularly in the presence of vibration or other disturbances at or near the resonance frequency.

10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130  
131  
132  
133  
134  
135  
136  
137  
138  
139  
140  
141  
142  
143  
144  
145  
146  
147  
148  
149  
150  
151  
152  
153  
154  
155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236  
237  
238  
239  
240  
241  
242  
243  
244  
245  
246  
247  
248  
249  
250  
251  
252  
253  
254  
255  
256  
257  
258  
259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
310  
311  
312  
313  
314  
315  
316  
317  
318  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
350  
351  
352  
353  
354  
355  
356  
357  
358  
359  
360  
361  
362  
363  
364  
365  
366  
367  
368  
369  
370  
371  
372  
373  
374  
375  
376  
377  
378  
379  
380  
381  
382  
383  
384  
385  
386  
387  
388  
389  
390  
391  
392  
393  
394  
395  
396  
397  
398  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
420  
421  
422  
423  
424  
425  
426  
427  
428  
429  
430  
431  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
460  
461  
462  
463  
464  
465  
466  
467  
468  
469  
470  
471  
472  
473  
474  
475  
476  
477  
478  
479  
480  
481  
482  
483  
484  
485  
486  
487  
488  
489  
490  
491  
492  
493  
494  
495  
496  
497  
498  
499  
500  
501  
502  
503  
504  
505  
506  
507  
508  
509  
510  
511  
512  
513  
514  
515  
516  
517  
518  
519  
520  
521  
522  
523  
524  
525  
526  
527  
528  
529  
530  
531  
532  
533  
534  
535  
536  
537  
538  
539  
540  
541  
542  
543  
544  
545  
546  
547  
548  
549  
550  
551  
552  
553  
554  
555  
556  
557  
558  
559  
560  
561  
562  
563  
564  
565  
566  
567  
568  
569  
570  
571  
572  
573  
574  
575  
576  
577  
578  
579  
580  
581  
582  
583  
584  
585  
586  
587  
588  
589  
590  
591  
592  
593  
594  
595  
596  
597  
598  
599  
600  
601  
602  
603  
604  
605  
606  
607  
608  
609  
610  
611  
612  
613  
614  
615  
616  
617  
618  
619  
620  
621  
622  
623  
624  
625  
626  
627  
628  
629  
630  
631  
632  
633  
634  
635  
636  
637  
638  
639  
640  
641  
642  
643  
644  
645  
646  
647  
648  
649  
650  
651  
652  
653  
654  
655  
656  
657  
658  
659  
660  
661  
662  
663  
664  
665  
666  
667  
668  
669  
670  
671  
672  
673  
674  
675  
676  
677  
678  
679  
680  
681  
682  
683  
684  
685  
686  
687  
688  
689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708  
709  
710  
711  
712  
713  
714  
715  
716  
717  
718  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
730  
731  
732  
733  
734  
735  
736  
737  
738  
739  
740  
741  
742  
743  
744  
745  
746  
747  
748  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759  
760  
761  
762  
763  
764  
765  
766  
767  
768  
769  
770  
771  
772  
773  
774  
775  
776  
777  
778  
779  
780  
781  
782  
783  
784  
785  
786  
787  
788  
789  
790  
791  
792  
793  
794  
795  
796  
797  
798  
799  
800  
801  
802  
803  
804  
805  
806  
807  
808  
809  
810  
811  
812  
813  
814  
815  
816  
817  
818  
819  
820  
821  
822  
823  
824  
825  
826  
827  
828  
829  
830  
831  
832  
833  
834  
835  
836  
837  
838  
839  
840  
841  
842  
843  
844  
845  
846  
847  
848  
849  
850  
851  
852  
853  
854  
855  
856  
857  
858  
859  
860  
861  
862  
863  
864  
865  
866  
867  
868  
869  
870  
871  
872  
873  
874  
875  
876  
877  
878  
879  
880  
881  
882  
883  
884  
885  
886  
887  
888  
889  
890  
891  
892  
893  
894  
895  
896  
897  
898  
899  
900  
901  
902  
903  
904  
905  
906  
907  
908  
909  
910  
911  
912  
913  
914  
915  
916  
917  
918  
919  
920  
921  
922  
923  
924  
925  
926  
927  
928  
929  
930  
931  
932  
933  
934  
935  
936  
937  
938  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
950  
951  
952  
953  
954  
955  
956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966  
967  
968  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978  
979  
980  
981  
982  
983  
984  
985  
986  
987  
988  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
999  
1000  
1001  
1002  
1003  
1004  
1005  
1006  
1007  
1008  
1009  
1010  
1011  
1012  
1013  
1014  
1015  
1016  
1017  
1018  
1019  
1020  
1021  
1022  
1023  
1024  
1025  
1026  
1027  
1028  
1029  
1030  
1031  
1032  
1033  
1034  
1035  
1036  
1037  
1038  
1039  
1040  
1041  
1042  
1043  
1044  
1045  
1046  
1047  
1048  
1049  
1050  
1051  
1052  
1053  
1054  
1055  
1056  
1057  
1058  
1059  
1060  
1061  
1062  
1063  
1064  
1065  
1066  
1067  
1068  
1069  
1070  
1071  
1072  
1073  
1074  
1075  
1076  
1077  
1078  
1079  
1080  
1081  
1082  
1083  
1084  
1085  
1086  
1087  
1088  
1089  
1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1099  
1100  
1101  
1102  
1103  
1104  
1105  
1106  
1107  
1108  
1109  
1110  
1111  
1112  
1113  
1114  
1115  
1116  
1117  
1118  
1119  
1120  
1121  
1122  
1123  
1124  
1125  
1126  
1127  
1128  
1129  
1130  
1131  
1132  
1133  
1134  
1135  
1136  
1137  
1138  
1139  
1140  
1141  
1142  
1143  
1144  
1145  
1146  
1147  
1148  
1149  
1150  
1151  
1152  
1153  
1154  
1155  
1156  
1157  
1158  
1159  
1160  
1161  
1162  
1163  
1164  
1165  
1166  
1167  
1168  
1169  
1170  
1171  
1172  
1173  
1174  
1175  
1176  
1177  
1178  
1179  
1180  
1181  
1182  
1183  
1184  
1185  
1186  
1187  
1188  
1189  
1190  
1191  
1192  
1193  
1194  
1195  
1196  
1197  
1198  
1199  
1200  
1201  
1202  
1203  
1204  
1205  
1206  
1207  
1208  
1209  
1210  
1211  
1212  
1213  
1214  
1215  
1216  
1217  
1218  
1219  
1220  
1221  
1222  
1223  
1224  
1225  
1226  
1227  
1228  
1229  
1230  
1231  
1232  
1233  
1234  
1235  
1236  
1237  
1238  
1239  
1240  
1241  
1242  
1243  
1244  
1245  
1246  
1247  
1248  
1249  
1250  
1251  
1252  
1253  
1254  
1255  
1256  
1257  
1258  
1259  
1260  
1261  
1262  
1263  
1264  
1265  
1266  
1267  
1268  
1269  
1270  
1271  
1272  
1273  
1274  
1275  
1276  
1277  
1278  
1279  
1280  
1281  
1282  
1283  
1284  
1285  
1286  
1287  
1288  
1289  
1290  
1291  
1292  
1293  
1294  
1295  
1296  
1297  
1298  
1299  
1300  
1301  
1302  
1303  
1304  
1305  
1306  
1307  
1308  
1309  
1310  
1311  
1312  
1313  
1314  
1315  
1316  
1317  
1318  
1319  
1320  
1321  
1322  
1323  
1324  
1325  
1326  
1327  
1328  
1329  
1330  
1331  
1332  
1333  
1334  
1335  
1336  
1337  
1338  
1339  
1340  
1341  
1342  
1343  
1344  
1345  
1346  
1347  
1348  
1349  
1350  
1351  
1352  
1353  
1354  
1355  
1356  
1357  
1358  
1359  
1360  
1361  
1362  
1363  
1364  
1365  
1366  
1367  
1368  
1369  
1370  
1371  
1372  
1373  
1374  
1375  
1376  
1377  
1378  
1379  
1380  
1381  
1382  
1383  
1384  
1385  
1386  
1387  
1388  
1389  
1390  
1391  
1392  
1393  
1394  
1395  
1396  
1397  
1398  
1399  
1400  
1401  
1402  
1403  
1404  
1405  
1406  
1407  
1408  
1409  
1410  
1411  
1412  
1413  
1414  
1415  
1416  
1417  
1418  
1419  
1420  
1421  
1422  
1423  
1424  
1425  
1426  
1427  
1428  
1429  
1430  
1431  
1432  
1433  
1434  
1435  
1436  
1437  
1438  
1439  
1440  
1441  
1442  
1443  
1444  
1445  
1446  
1447  
1448  
1449  
1450  
1451  
1452  
1453  
1454  
1455  
1456  
1457  
1458  
1459  
1460  
1461  
1462  
1463  
1464  
1465  
1466  
1467  
1468  
1469  
1470  
1471  
1472  
1473  
1474  
1475  
1476  
1477  
1478  
1479  
1480  
1481  
1482  
1483  
1484  
1485  
1486  
1487  
1488  
1489  
1490  
1491  
1492  
1493  
1494  
1495  
1496  
1497  
1498  
1499  
1500  
1501  
1502  
1503  
1504  
1505  
1506  
1507  
1508  
1509  
1510  
1511  
1512  
1513  
1514  
1515  
1516  
1517  
1518  
1519  
1520  
1521  
1522  
1523  
1524  
1525  
1526  
1527  
1528  
1529  
1530  
1531  
1532  
1533  
1534  
1535  
1536  
1537  
1538  
1539  
1540  
1541  
1542  
1543  
1544  
1545  
1546  
1547  
1548  
1549  
1550  
1551  
1552  
1553  
1554  
1555  
1556  
1557  
1558  
1559  
1560  
1561  
1562  
1563  
1564  
1565  
1566  
1567  
1568  
1569  
1570  
1571  
1572  
1573  
1574  
1575  
1576  
1577  
1578  
1579  
1580  
1581  
1582  
1583  
1584  
1585  
1586  
1587  
1588  
1589  
1590  
1591  
1592  
1593  
1594  
1595  
1596  
1597  
1598  
1599  
1600  
1601  
1602  
1603  
1604  
1605  
1606  
1607  
1608  
1609  
1610  
1611  
1612  
1613  
1614  
1615  
1616  
1617  
1618  
1619  
1620  
1621  
1622  
1623  
1624  
1625  
1626  
1627  
1628  
1629  
1630  
1631  
1632  
1633  
1634  
1635  
1636  
1637  
1638  
1639  
1640  
1641  
1642  
1643  
1644  
1645  
1646  
1647  
1648  
1649  
1650  
1651  
1652  
1653  
1654  
1655  
1656  
1657  
1658  
1659  
1660  
1661  
1662  
1663  
1664  
1665  
1666  
1667  
1668  
1669  
1670  
1671  
1672  
1673  
1674  
1675  
1676  
1677  
1678  
1679  
1680  
1681  
1682  
1683  
1684  
1685  
1686  
1687  
1688  
1689  
1690  
1691  
1692  
1693  
1694  
1695  
1696  
1697  
1698  
1699  
1700  
1701  
1702  
1703  
1704  
1705  
1706  
1707  
1708  
1709  
1710  
1711  
1712  
1713  
1714  
1715  
1716  
1717  
1718  
1719  
1720  
1721  
1722  
1723  
1724  
1725  
1726  
1727  
1728  
1729  
1730  
1731  
1732  
1733  
1734  
1735  
1736  
1737  
1738  
1739  
1740  
1741  
1742  
1743  
1744  
1745  
1746  
1747  
1748  
1749  
1750  
1751  
1752  
1753  
1754  
1755  
1756  
1757  
1758  
1759  
1760  
1761  
1762  
1763  
1764  
1765  
1766  
1767  
1768  
1769  
1770  
1771  
1772  
1773  
1774  
1775  
1776  
1777  
1778  
1779  
1780  
1781  
1782  
1783  
1784  
1785  
1786  
1787  
1788  
1789  
1790  
1791  
1792  
1793  
1794  
1795  
1796  
1797  
1798  
1799  
1800  
1801  
1802  
1803  
1804  
1805  
1806  
1807  
1808  
1809  
1810  
1811  
1812  
1813  
1814  
1815  
1816  
1817  
1818  
1819  
1820  
1821  
1822  
1823  
1824  
1825  
1826  
1827  
1828  
1829  
1830  
1831  
1832  
1833  
1834  
1835  
1836  
1837  
1838  
1839  
1840  
1841  
1842  
1843  
1844  
1845  
1846  
1847  
1848  
1849  
1850  
1851  
1852  
1853  
1854  
1855  
1856  
1857  
1858  
1859  
1860  
1861  
1862  
1863  
1864  
1865  
1866  
1867  
1868  
1869  
1870  
1871  
1872  
1873  
1874  
1875  
1876  
1877  
1878  
1879  
1880  
1881  
1882  
1883  
1884  
1885  
1886  
1887  
1888  
1889  
1890  
1891  
1892  
1893  
1894  
1895  
1896  
1897  
1898  
1899  
1900  
1901  
1902  
1903  
1904  
1905  
1906  
1907  
1908  
1909  
1910  
1911  
1912  
1913  
1914  
1915  
1916  
1917  
1918  
1919  
1920  
1921  
1922  
1923  
1924  
1925  
1926  
1927  
1928  
1929  
1930  
1931  
1932  
1933  
1934  
1935  
1936  
1937  
1938  
1939  
1940  
1941  
1942  
1943  
1944  
1945  
1946  
1947  
1948  
1949  
1950  
1951  
1952  
1953  
1954  
1955  
1956  
1957  
1958  
1959  
1960  
1961  
1962  
1963  
1964  
1965  
1966  
1967  
1968  
1969  
1970  
1971  
1972  
1973  
1974  
1975  
1976  
1977  
1978  
1979  
1980  
1981  
1982  
1983  
1984  
1985  
1986  
1987  
1988  
1989  
1990  
1991  
1992  
1993  
1994  
1995  
1996  
1997  
1998  
1999  
2000  
2001  
2002  
2003  
2004  
2005  
2006  
2007  
2008  
2009  
2010  
2011  
2012  
2013  
2014  
2015  
2016  
2017  
2018  
2019  
2020  
2021  
2022  
2023  
2024  
2025  
2026  
2027  
2028  
2029  
2030  
2031  
2032  
2033  
2034  
2035  
2036  
2037  
2038  
2039  
2040  
2041  
2042  
2043  
2044  
2045  
2046  
2047  
2048  
2049  
2050  
2051  
2052  
2053  
2054  
2055  
2056  
2057  
2058  
2059  
2060  
2061  
2062  
2063  
2064  
2065  
2066  
2067  
2068  
2069  
2070  
2071  
2072  
2073  
2074  
2075  
2076  
2077  
2078  
2079  
2080  
2081  
2082  
2083  
2084  
2085  
2086  
2087  
2088  
2089  
2090  
2091  
2092  
2093  
2094  
2095  
2096  
2097  
2098  
2099  
2100  
2101  
2102  
2103  
2104  
2105  
2106  
2107  
2108  
2109  
2110  
2111  
2112  
2113  
2114  
2115  
2116  
2117  
2118  
2119  
2120  
2121  
2122  
2123  
2124  
2125  
2126  
2127  
2128  
2129  
2130  
2131  
2132  
2133  
2134  
2135  
2136  
2137  
2138  
2139  
2140  
2141  
2142  
2143  
2144  
2145  
2146  
2147  
2148  
2149  
2150  
2151  
2152  
2153  
2154  
2155  
2156  
2157  
2158  
2159  
2160  
2161  
2162  
2163  
2164  
2165  
2166  
2167  
2168  
2169  
2170  
2171  
2172  
2173  
2174  
2175  
2176  
2177  
2178  
2179  
2180  
2181  
2182  
2183  
2184  
2185  
2186  
2187  
2188  
2189  
2190  
2191  
2192  
2193  
2194  
2195  
2196  
2197  
2198  
2199  
2200  
2201  
2202  
2203  
2204  
2205  
2206  
2207  
2208  
2209  
2210  
2211  
2212  
2213  
2214  
2215  
2216  
2217  
2218  
2219  
2220  
2221  
2222  
2223  
2224  
2225  
2226  
2227  
2228  
2229  
2230  
2231  
2232  
2233  
2234  
2235  
2236  
2237  
2238  
2239